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Experimental Investigation of the Performance of Evacuated-Tube Solar Collectors under Eastern Mediterranean Climatic Conditions

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Abstract

Experimental investigation of the overall performance of solar collectors under local weather conditions as encountered along the eastern coast of the Mediterranean Sea is carried out for two kinds of evacuated-tube solar collectors, namely, the water-in-glass tubes and the heat-pipe designs. An experimental set-up, involving full scale collectors made of a row of 20 evacuated tubes and their tank, and a circulation system with measurement tools, was constructed and used. The experiments were carried out during the period of November to January, i.e. under winter-like conditions, at days where the sky was almost clear with some clouds scattered here and there. The results show that the heat-pipe-based collectors are better than the water-in-glass designs and their efficiency is almost 15 to 20% higher. Their payback periods are however, much higher owing to their larger initial cost in the local market.

Keywords: Solar Energy; Solar Collector; Evacuated Tube; Efficiency; Heat Pipe.

1. Introduction

Solar water heaters are more and more used worldwide, and the evacuated-tube designs are the most popular due to their simplicity and better overall performance over their flat-plate counterparts, especially in adverse weather conditions. Many evacuated-tube designs have been developed and are being used

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Nomenclature

A	Surface area of collector, m^2
a,b	Correlation coefficients
c_p	Specific heat at constant pressure, J/kg.°C
G	Irradiation, W/m^2
$\dot{m}$	Mass flow rate, kg/s
Q	Heat rate, W
T_a	Ambient temperature, °C
T_{in}	Inlet temperature, °C
T_m	Mean temperature, °C
T_{out}	Outlet temperature, °C
η	Efficiency
η_0	Correlation coefficient

among which the water-in-glass design is very popular because of its low cost and simple manufacturing and installation procedures. Another design uses a heat-pipe system with an intermediate fluid used to carry the heat from the heating elements to the tank [1]. In this case the working fluid undergoes a phase change operation while it is transported up and down.

A water-in-glass tube-based collector consists of a set of glass tubes connected to a shell or tank. Each tube is surrounded by a second glass tube of a larger diameter. The annular space between the tubes is evacuated in order to minimize the heat losses. The working fluid, generally water, flows from the tank to the tubes, captures heat, and then flows back to the tank by a natural circulation mechanism [2]. Various investigations have been conducted to characterize the overall performance of water-in-glass evacuated tube collectors and the results show that the overall efficiency is in the range of 50 to 60% [3-5]. Advanced numerical techniques have been also used to investigate the performance and to find possible ways to improve existing designs of evacuated tubes [6].

A heat-pipe based collector involves generally a similar set of tubes connected to a tank. Each tube is made of a finned copper pipe (heat pipe) surrounded by a glass tube and the annular space in between is evacuated. The heat pipe is a closed container consisting of a capillary wick structure and a small amount of vaporizable fluid. It is based on an evaporating-condensing cycle involving an evaporation phase using the solar heat followed by a condensation phase in which the heat is released to the metal plate or heat sink located at the top of the tube or at the junction tank-tubes. The working fluid flows by natural circulation between the two phases in order to transport the heat as needed [7-8].

Evaluation of the overall performance of solar collectors is usually carried out experimentally using proven procedures according to international standards [9-11] and many correlations have been developed for the purpose of predicting the overall efficiency under various climatic conditions. Various studies have been conducted to evaluate the thermal performance of evacuated-tube solar collectors and to compare them to their flat plate counterparts [12].

Evacuated-tube collectors are generally manufactured in standard sizes and are mounted inclined at an angle, which is to be estimated using the latitude of the location under consideration. Various parameters may affect the overall performance of collectors among which the tilt angle, the weather conditions, the collector dimensions, etc. It is well admitted that the best performance is achieved when the sun rays hit the collector elements at right angle in order to maximize the energy absorption mechanism [13].

The objective of the present study is to investigate the overall performance of solar collectors under local weather conditions as encountered along the eastern coast of the Mediterranean Sea. Two kinds of collectors are considered and tested experimentally: the water-in-glass and heat pipe designs. The results are validated versus established experimental data and some design considerations and conclusions are presented as needed.

2. Experimental Set-Up

An experimental set-up was designed and installed on a parking area facing the engineering building in the main campus of Notre Dame University-Louaize located in Zouk-Mosbeh, a hilly area to the north of Beirut with an altitude of around 150 m. Figure 1 shows the entire system with a standard water-in-glass collector made of 20 evacuated tubes and the storage tank. The experimental set-up is a closed loop circuit with the required components and measurement tools as sketched in figure 1 too.

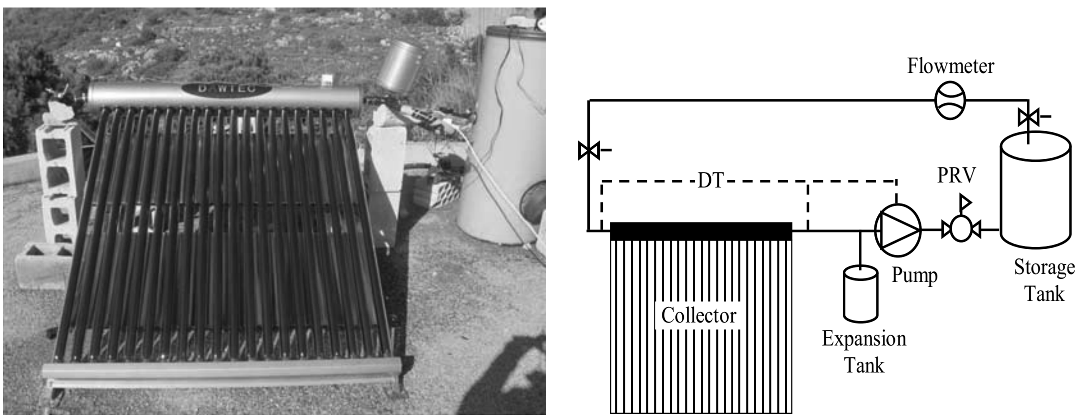

Fig. 1. Experimental test rig and its schematic.

A circulation pump is used to circulate the working fluid between the collector and the storage tank. The solar storage tank is a 150l insulated vessel. It is equipped with a set of pipe connections, two located near the top of the tank and two located near the bottom. To take advantage of storage tank stratification, pipes supplying the collector array and the cold-water inlet should be connected to the bottom ports, and the pipes returning to the tank from the collector array and hot water supplied to the load should be connected to the ports near the top. Instrumentation openings are also required as well as openings for relief valves, drains, and the like.

A differential temperature controller (DT), that measures the inlet and outlet temperatures of the collector, controls the flow in the system by switching the circulation pump on when the temperature in the storage tank is lower than that of the collector by 10°C. On the other hand, the pump is switched off when the collector temperature is higher than that of the storage tank by 2°C in order to prevent reverse thermosiphoning.

Stagnation is a condition that may occur when the system is deactivated while fluid is contained in the collectors during periods of solar insolation. For example, on a sunny day stagnation temperatures in an evacuated heat pipe tube collector can exceed 200°C, leading to vaporization of the transport fluid within the collector and excessive pressure build up in the system piping. In the case of a closed-loop system, it is important to ensure that all components in the collector loop can withstand these temperatures and pressures. A pressure relief valve and an expansion tank are used to protect the system components and control devices.

An air vent placed at the top of the collector allows air that has been released inside the system to be purged. Drain valves are installed at the bottom of the storage tank in order to fill and empty the circuit when needed. The piping network is insulated by a layer of polyurethane foam in order to minimize heat losses. A digital flowmeter is included in the circuit for the purpose of measuring the flowrate inside the system.

Finally, solar radiation was measured by a pyranometer, connected to a datalogger. Readings were taken manually every 15 minutes at stable flow conditions. The temperature readings were taken from the controller, and double checked by the reading taken from the temperature difference reading option in the multifunctional flow meter used.

A representative set of data collected with the heat pipe collector tilted at 30° is shown in figure 2. The different quantities recorded are the time at which the measurement is taken, the irradiation, the flow rate, the inlet and outlet temperatures of the collector and the ambient temperature. It is to be noticed that the maximum temperature is achieved in the early afternoon at a time when the solar irradiation starts to decrease.

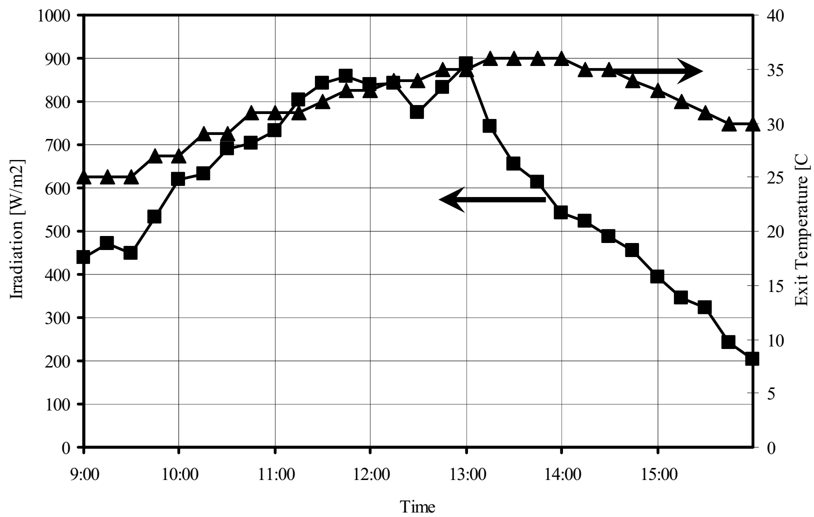

Fig. 2. Experimental irradiation and exit temperature of collector for a typical day (Nov. 23) from 9:00 to 16:00.

3. Theoretical Analysis

In order to determine the efficiency parameters of solar thermal collectors, two different procedures can be used: the steady state test method and the quasi dynamic test method.

During the steady state test, all boundary conditions such as solar irradiation, ambient temperature and collector inlet temperature shall be maintained constant. After recording data points over a representative range of operating conditions, the collector efficiency curve can be determined by means of multi-linear regression techniques.

During the quasi dynamic test, the boundary conditions are left free to vary. Based on a series of measurements, specific collector parameters are determined, as well. With the quasi dynamic test method, additional parameters such as the heat capacity of the collector and the incident angle modifier coefficient can be determined in addition to the efficiency curve.

In both techniques, the basic concept is to expose the collector to solar radiation and measure the inlet and outlet temperatures of the working fluid flowing with a known flow rate. The heat rate gained by the fluid is then given by

$$Q = \dot{m} c_p \left(T_{out} - T_{in}\right) \tag{1}$$

The source of heat in a solar collector is solar energy and the input power is usually the irradiation, G, received on the surface of the collector, absorbed and then transferred to the working fluid. By dividing the net power output by the input power, an overall efficiency can be defined. Such efficiency is generally considered as instantaneous efficiency because it is a function of instantaneous operating conditions including local climatic parameters like the ambient temperature, the wind speed, etc.

$$\eta = \left[\dot{m} c_p \left(T_{out} - T_{in}\right)\right] / A_c G \tag{2}$$

The same net power output can be written in terms of quantities representing the heat transfer mechanism, or the heat input minus the heat losses, as [14]

$$Q = A_c F_R \left[G - U_L \left(T_m - T_a\right)\right] \tag{3}$$

where F_R is the collector heat removal factor and U_L is the overall heat loss coefficient. T_m is a mean temperature of the working fluid flowing inside the collector, generally taken as the average between the inlet and outlet temperatures of the collector. Combining the heat rate given by equation (3) with the definition of the efficiency, and noting that U_L is generally a function of temperature, leads to the following expression

$$\eta = \eta_0 - a \frac{\left(T_m - T_a\right)}{G} - b \left(\frac{T_m - T_a}{G}\right)^2 \tag{4}$$

in which η_0, a, and b, are constants to be evaluated either analytically or experimentally.

Many experimental correlations have been developed to evaluate the overall efficiency of evacuated tube solar collectors. Developing the correlation is part of the testing process for every collector to be certified and different manufacturers and testing authorities are publishing their own correlations [15]. Typical correlations used for the heat pipe system under consideration in the present study are listed in table 1.

Table 1. Typical experimental coefficients of efficiency correlations for heat-pipe collecotrs.

Correlation	η_0,	a	b	Source
Manufacturer	0.80	1.20	0.007	Manufacturer recommendation
Teknikum	0.84	2.02	0.0046	Teknikum Rapperswill [16]
Florida	0.81	1.23	0.0122	FSEC [16]

The overall efficiency of water-in-glass tubes is described by a similar correlation [17]

$$\eta = 0.58 - 0.9271\frac{(T_m - T_a)}{G} - 0.0067\frac{(T_m - T_a)^2}{G} \quad (5)$$

The constants have been slightly adjusted recently [18] and the result is a correlation predicting slightly lower efficiencies than the values given by eq. 5.

It is to be noticed that the last term of equations 4 and 5 plays a very minor role in the final values of efficiency and some authors did drop it ending up with linear relationships for η [16].

4. Results & Discussion

The experiments were conducted over a period of three months, from November to January, on a parking area located in Notre Dame University main campus in Zouk-Mosbeh, north of Beirut, Lebanon. Like elsewhere along the eastern Mediterranean cost, the site is sunny most of the year with winter-like conditions prevailing from time to time. All tests were conducted during relatively cold days with the sun shining and some clouds scattered here and there.

Figure 3 shows the results for both the heat-pipe and the water-in-glass collectors tilted at an angle of 45° compared to similar experimental results derived from manufacturer recommendations or independent testing correlations as given in table 1. The agreement is very good and the trends are similar for both sets of results. The slight differences are most probably due to the prevailing climatic conditions which play a major role in the process of heat loss to the surroundings. The slope of the lines is a direct representation of the heat loss coefficient as shown in equation 3.

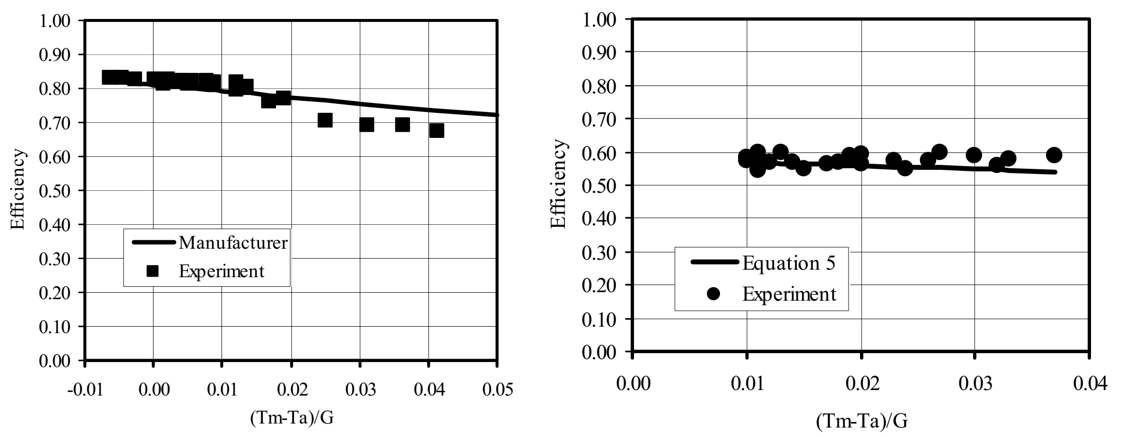

Fig. 3. Validation of the present experimental results for heat pipe collectors (left) and water-in-glass collectors (right).

The tilt angle of the collector is expected to have a non-negligible effect on the overall performance of the system. It is well known that the best performance is achieved when the sun rays hit the collector surface at right angle. To investigate such an effect, various tests have been conducted at different tilt angles and for both the heat-pipe and water-in-glass collectors. The results are shown in figure 4 for three angles, namely, 30°, 45° and 55°. The influence of the tilt angle on the collector efficiency seems non negligible for both the heat-pipe and the water-in-glass collectors. This influence is clear towards the ends of the curves, i.e., at low irradiation where the energy input becomes relatively low and its capture very critical. At high irradiation rates all inclination angles lead nearly to the same overall performance for both kinds of collectors.

The fact that both collectors are largely affected by the tilt angle at low radiation levels can be explained by the nature of the heat transport mechanism inside the tubes which is mainly by natural convection. The free convection mechanism is usually highly affected by the aspect ratio of the enclosure and the evacuated tubes used are very long compared to their diameter. As a result, the effectiveness of the buoyancy forces in transporting the working fluid over the entire length of the tube decreases and non-negligible dead zones appear at the bottom of the tubes contributing to the decrease of their effective length. Such a process has been clearly identified for the water-in-glass tubes [3, 6] and it is expected that the heat-pipe collectors will experience a similar drawback although the working fluid is vaporized and transported in a gas phase instead of liquid. Even though, the transport of vapor is much easier, the fact that the diameter of the heat pipe is relatively small may hinder the transport process itself contributing to the decrease of the effective length mentioned above. This idea is still to be investigated in order to improve the understanding of the two phase fluid flow inside a heat pipe.

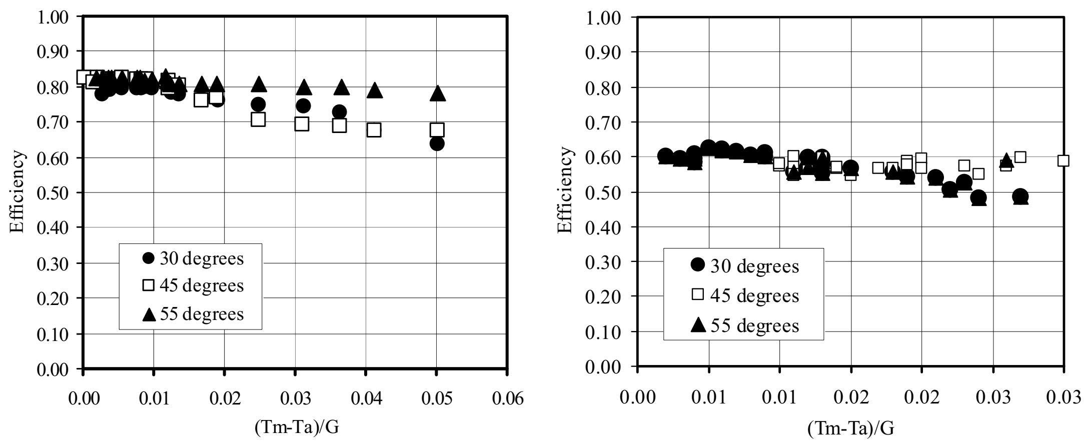

Fig. 4. Overall performance as a function of the tilt angle for heat pipe collectors (left) and water-in-glass collectors (right).

Figure 5 shows a comparison between the heat-pipe collector and its water-in-glass counterpart. The overall efficiency of the heat-pipe collectors is almost 15 to 20% higher than that of water-in-glass collectors. Of course, other parameters play also a role in this lower efficiency and should be considered when trying to improve the design of water-in-glass collectors. Some examples of such parameters are the design of the absorption surface itself and a better control of the heat losses [6].

Despite their lower efficiency, water-in-glass collectors are more widely used owing mainly to their much lower cost, which is a key factor in promoting the use of solar energy worldwide and behind it renewable energies in general. Typical design calculation applied to real life systems located in the region shows that the payback periods are almost three to four times more for the heat-pipe collectors. This remark may change if the design is to be based on different geographic areas and/or different climatic conditions, especially in terms of number of sunny days per years.

All experimental results were analyzed in order to see whether it is possible to come up with a single correlation describing the overall performance of evacuated-tube solar collectors. The result is a second order polynomial curve given by

$$\eta = 0.8097 - 1.7828\frac{(T_m - T_a)}{G} + 0.0119\left(\frac{T_m - T_a}{G}\right)^2 \qquad (6)$$

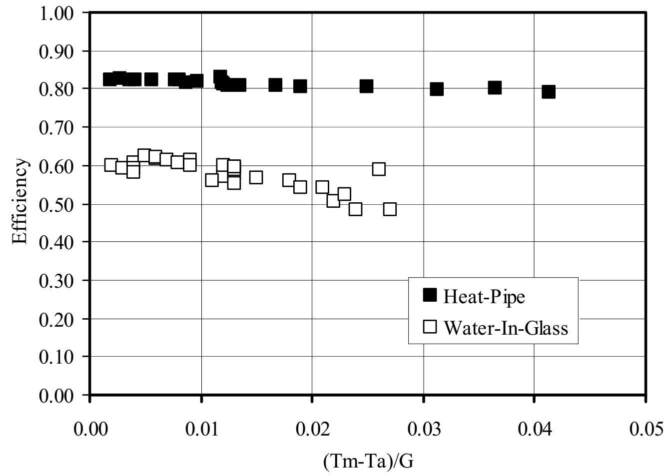

Fig. 5. Performance of heat-pipe vs. water-in-glass collectors.

This correlation is valid for the heat-pipe collector only since the experimental data for the water-in-glass collectors are not enough to generate a statistically meaningful relationship. To further validate the correlation (6), it is plotted in figure 6 and compared to other similar correlation collected from the manufacturer literature. All correlations give similar trends with more or less the same slope. The slight variations may be explained by changes in local operating conditions as well as experimental uncertainties.

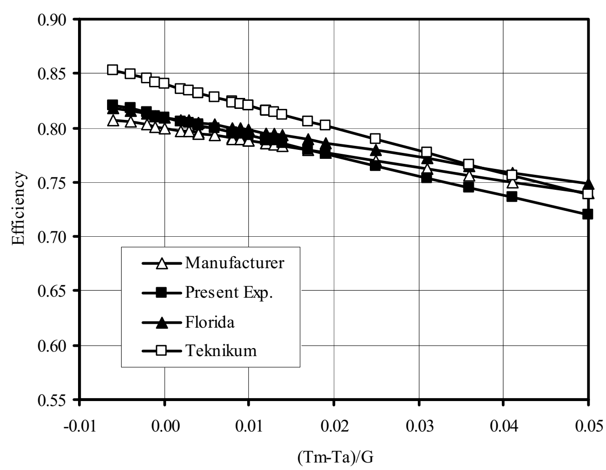

Fig. 6. Comparison of correlation 6 with similar correlations for heat-pipe collectors (table 1).

5. Conclusions

Various experiments were conducted in order to characterize the overall performance of evacuated-tube solar collectors as used in the local Lebanese market. The results are in good agreement with similar results published by manufacturers and independent testing authorities. The main conclusion is that the heat-pipe collectors have a much better efficiency than the water-in-glass collectors. Those later are however, more widely used locally owing to their lowest initial cost and their relatively short payback periods.

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References

[1] Kalogirou S.A, Solar thermal collectors and applications, *Progress in Energy and Combustion Science*, 2004, **30**:231-295.

[2] Morrison G.L., Budihardjo I., Behnia M., Water-in-glass evacuated tube solar water heaters, *Solar Energy*, 2004, **76**:135-140.

[3] Morrison G.L., Budihardjo I., Behnia M., Measurement and simulation of flow rate in a water-in-glass evacuated tube solar water heater, *Solar Energy*, 2005, **78**:257-267.

[4] Kim Y., Seo T., Thermal performance comparisons of the glass evacuated tube solar collectors with shapes of absorber tube, *Renewable Energy*, 2007, **32**:772-795.

[5] Zhang X.R., Yamaguchi H., An experimental study on evacuated tube solar collector using supercritical CO_2, *Applied Thermal Engineering*, 2008, **28**:1225-1233.

[6] Hayek M., Investigation of evacuated-tube solar collectors performance using computational fluid dynamics, *Proceedings of ACTEA09*, 2009, pp.240-244.

[7] Walker A., Mahjouri F., Stiteler R., Evacuated-Tube Heat-Pipe Solar Collectors Applied to the Recirculation Loop in a Federal Building, NREL/CP-710-36149, 2004.

[8] Kim Y., Seo T., Thermal performances comparisons of the glass evacuated tube solar collectors with shapes of absorber tube, *Renewable Energy*, 2007, **32**:772–795.

[9] ASHRAE, Methods of Testing to Determine the Thermal Performance of Solar Collectors. ASHRAE 93, 2010.

[10] Hill, J.E., Streed E.R, A method of testing for rating solar collectors based on thermal performance, *Solar Energy*, 1976, **18**:421-429.

[11] Proctor D., A generalized method for testing all glasses of solar collectors, II: Evaluation of collector thermal constants, *Solar Energy*, 1984, **32**:387-394.

[12] Zambolin E., Del Col D., Experimental analysis of thermal performance of flat plate and evacuated tube solar collectors in stationary standard and daily conditions, *Solar Energy*, 2010, **84**:1382–1396.

[13] Tang R., Gao W., Yu Y., Chen H., Optimal tilt-angles of all-glass evacuated tube solar collectors, *Energy*, 2009, **34**:1387–1395.

[14] Duffie J.A., Beckman W., *Solar engineering of thermal processes,* 3rd ed., J. Wiley & Sons; 2006.

[15] Institut für Solartechnik SPF, Switzerland; http://www.solarenergy.ch/, last accessed, February 04, 2010.

[16] Mahjouri F., Vacuum tube liquid-vapor (heat-pipe) collectors, ThermoTehcnologies (http://www.thermotechs.com/).

[17] Budihardjo I., Morrison G.L., Behnia M., Development of TRNSYS models for predicting the performance of water-in-glass evacuated tube solar water heaters in Australia, Proceedings of ANSZES Annual Conference, 2003.

[18] Budihardjo I., Morrison G.L., Performance of water-in-glass evacuated tube solar water heaters, *Solar Energy*, 2009, **83**:49–56.